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# Dynamic Capacity Reduction of Railway Prestressed Concrete due to Surface Abrasions Considering the Effects of Strain Rate and Prestressing Losses

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**Abstract** In reality, railway prestressed concrete sleepers frequently experience significant aggressive loading conditions and harsh environments. Especially in sharp curves, lateral loading of train wheels in combination with incompressible hydraulic pressure aggravates the lateral oscillation and abrade the surface of sleepers right underneath the rail seats. Many investigators in the past have proposed various material models to improve abrasive resistance characteristics but those have been mostly applied to the new products using novel materials such as fibre-reinforced concrete. On the other hand, prestressed concrete sleepers have been used for over 50 years and they have worn over time. This paper highlights the dynamic capacity evaluation of worn sleepers, which will lead to predictive models that could be realistically applied to asset management of railway lines. This paper presents an investigation into the structural capacity reduction in worn railway prestressed concrete sleepers considering the effects of strain rate and loss of prestressing steel. RESPONSE2000 has been used to evaluate the residual dynamic capacity based on the modified compression field theory. Unprecedented parametric studies have been carried out to determine the influences of uniform and gradient prestress losses on prestressed concrete capacity. The study results exhibit the level of wear and tear, which is critical to the dynamic integrity of sleepers required for immediate replacement. The outcome of this study will help improve the practical maintenance and monitoring technology in railway industry.

**Keywords:** prestressed concrete sleepers, abrasion, railseat abrasion, soffit abrasion, strain rate, prestressing loss

## 1. Introduction

Railway sleepers (also called ‘railroad tie’ in North America) are a main part of railway track structures. Railway sleepers embedded in ballasted railway tracks are laid to support the rails. Remarkably, railway prestressed concrete sleepers have been used in railway industry for over 50 years,<sup>1,2</sup>. The sleepers can be typically made of timber, concrete, steel or other materials,<sup>3</sup>. The duty of sleeper is to redistribute loads from the rails to the underlying ballast bed and to

secure rail gauge and enable safe passages of rolling stocks. It is interesting to note that railway sleepers are a structural and safety critical component in railway track systems, see Refs. 4-9.

Railway track structures often experience impact loading conditions due to wheel/rail interactions associated with abnormalities,<sup>10</sup> in either a wheel or a rail. Generally, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called “wheel fly”, will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse acting after the static wheel load is removed.

Previous work revealed that most of the numerical and analytical models employed the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. In practice, the lateral force is less than 20% of vertical force and the anchorage of fastening has been designed to take care of lateral actions,<sup>11</sup>. In fact, field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the support condition induced by ballast packing and tamping,<sup>12-15</sup>. However, it is still questionable at large whether modern ballast tamping process is effective and it could enable adequate symmetrical support for sleeper at railseat areas. Over time, ballast densification at railseats is induced by dynamic broadband behaviours and the sleeper mid-span comes into contact or is fully supported by ballast until the track geometry is restored by resurfacing activity (i.e. re-tamping),<sup>16</sup>. At railseat, the dynamic loading condition gives a high change that the bottom of sleeper (or called ‘soffit’) may experience aggressive abrasive force, wearing out the materials in the region.

Although, the critical literature review reveals that the dynamic behaviour of railway sleepers has been studied, see Refs. 17-18, the considerations of its behaviour when the sleepers are deteriorated by excessive wears,<sup>19-21</sup> have not been fully investigated. Most common wears are railseat and soffit abrasion at railseat, which can be normally observed in the fields. Although it is clear that the railway sleepers can experience dynamic lateral wears, such the aspect has never been fully investigated. This paper is the world first to investigate and present an advanced railway concrete sleeper modelling capable of parametric analysis into the effect of surface abrasion considering strain rate and prestressing loss effects on the dynamic behaviors of railway sleepers. The emphasis of this study has been placed on the impact capacity of the sleepers with abrasion. The improve understanding from this paper will help update the practical maintenance issues in railway industry.

## **2. Prediction for Ultimate Moment Capacity**

### **2.1. Modified compression field theory**

In this study, the ultimate moment has been used to represent the capacity of prestressed concrete sleepers. The moment capacities are predicted by the modified compression field theory using Response-2000,<sup>22</sup>. This theory is capable of predicting the behaviour of reinforced concrete subjected to in-plane shear and normal stresses. The concrete stresses in principal directions along with prestressing steel are considered in only axial direction and uncracked portion will carry on to sustain a load in the analysis, see Ref. 23. The assumptions of this theory are that the deformation plane section

remains plane after loading and there is no transverse clamping stress across the depth of the section. Also, the section can be failed in only pure bending or shear-bending modes.

## 2.2. Effect of strain and loading rates

Based on the assumption of perfect bond between prestressing wires and concrete, the strain rate plays an important role in material strengths. In this study, strain rate are varied to study the effect of strain rate to moment capacity under impact loading. The dynamic material properties of concrete and prestressing wires can be determined as follows,<sup>24</sup>.

Concrete:

$$\frac{f'_{c,dyn}}{f'_{c,st}} = 1.49 + 0.268 \log_{10} \dot{\epsilon} + 0.035 [\log_{10} \dot{\epsilon}]^2 \quad (2.2.1)$$

Prestressing wires:

$$\frac{f_{y,dyn}}{f_{y,st}} = 10^{0.38 \log_{10} \dot{\epsilon} - 0.258} + 0.993 \quad (2.2.2)$$

Where  $f_{y,dyn}$  is the dynamic upper yield point stress,  $f'_{c,st}$  is the static upper yield point stress of prestressing wires (about 0.84 times proof stress), and  $\dot{\epsilon}$  is the strain rate in tendon.

## 3. Material properties

In this study, two positions of prestressed concrete sleepers, which are normal position and inverse position, are considered in order to evaluate the positive and negative ultimate moment capacities, respectively, as shown in Fig. 1. The sleeper considered is designed for board gauge at the capacity of 25 tonne. The 22 wires of 5mm diameter are taken into account. The unit shown in Fig. 1 is millimetre.

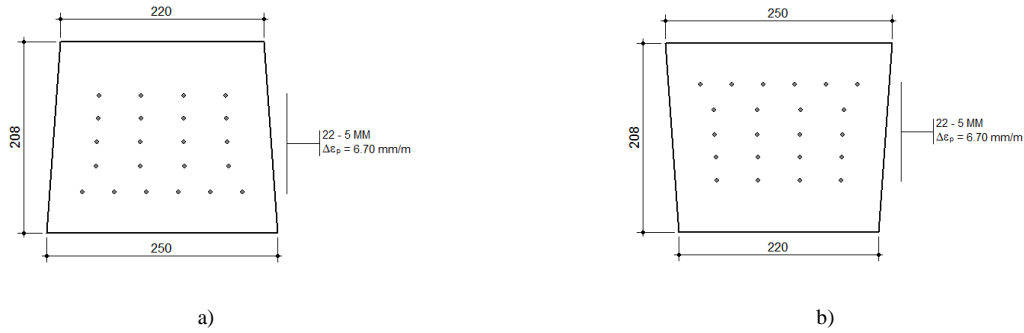


Fig. 1. Prestressed concrete sleepers dimension at rail seat in a) Normal position b) Inverse position

### 3.1. Static

The dimension and shape of prestressed concrete sleepers are shown in Fig. 1. The high strength concrete was used with the design cylinder compressive strength of 55 MPa. The stress-strain curve of concrete derived by Vecchio and Collin,<sup>25</sup> was used in this study, as shown in Fig. 2. The 22- prestressing steels used were the high ultimate strength with rupture ultimate strength of 1860 MPa, as shown in Fig. 2. The initial elastic modulus of prestressing steel was 20000 MPa.

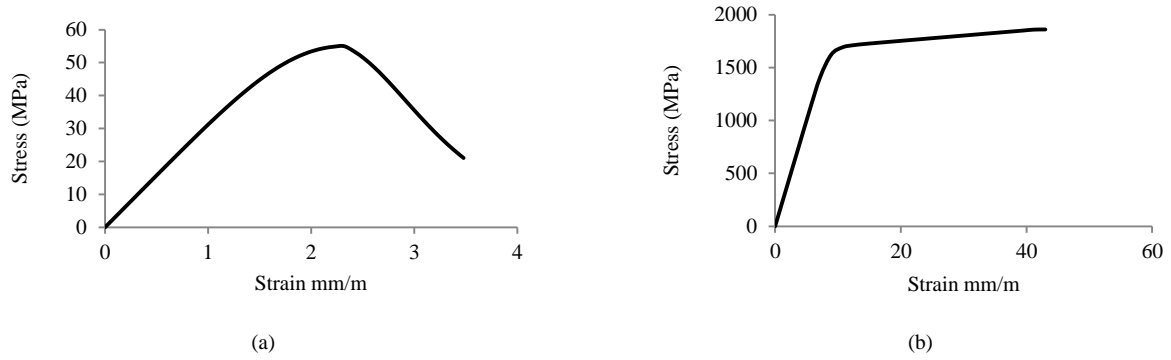


Fig. 2. Stress-strain curve of a) concrete b) steel

### 3.2. Dynamic

The prediction of moment capacity has been carried out using the data obtained from the previous experiments see Ref. 26, 27. It should be noted that the average total duration of impact forces is about 4 ms. In this study, the strain rate of concrete is varied from  $2 \text{ s}^{-1}$  to  $8 \text{ s}^{-1}$ . It is well known that the dynamic ultimate strain of prestressing steel is about 0.02, and the total duration of impact force influencing the steel fibre is roughly from 6 ms. This is because the impact stress wave delays during the stress propagation and will be impeded through concrete,<sup>24</sup>. Thus, the strain rate of prestressing wires are estimated to be between  $6 \text{ s}^{-1}$  and  $12 \text{ s}^{-1}$ . The dynamic strength of materials can be obtained as the input for the sectional analysis using equation (1) and (2). The 4 pairs of strain rates variations are used in this study, as shown in Table 1.

Table 1. Strain rate variations under impact loading.

Material	A	B	C	D
Concrete	2	4	6	8
Prestressing wires	6	8	10	12

## 4. Results and Discussions

Using the material properties from section 3, the ultimate moment capacities of worn prestressed concrete sleepers, which are railseat abrasion and soffit abrasion, under static loading and impact loading can be illustrated in this section. To predict the moment capacity of sleepers, full moment-curvature response is analyzed by applying moment with incremental until the end of analysis so that the member would be fail in bending mode. As for railseat abrasion, the depth of prestressed concrete sleepers is reduced by 10 mm, 20 mm, and 30 mm, respectively, at the top surface. In term of soffit abrasion, the depth is reduced by 15 mm, 30 mm, and 45 mm until the position of bottom layer of prestressing steel. It is assumed that the steel still remain at the bottom of sleeper cross section.

### 4.1. Static analysis

Table 2 demonstrates ultimate moment capacities of worn prestressed concrete sleepers under static loading. It exhibits that railseat abrasions play a dominant role on positive moment capacity of the worn sleepers, whilst negative moment capacity does not have similar effects. Moreover, it can be observed that soffit abrasion plays a little role on positive

115 moment capacities of the worn sleepers. On the other hand, this mechanism can be a significant effect on negative  
 116 moment capacity reduction.

117 Table 2. Ultimate moment capacities of prestressed concrete sleepers under static loading.

Worn depth (mm)		Recorded moment capacity (kNm)	
Railseat	Soffit	Positive	Negative
No abrasion		59.30	47.50
10	0	52.50	47.40
20	0	45.80	47.30
30	0	39.40	47.00
0	15	59.00	37.40
0	30	58.50	28.10
0	45	58.00	19.80

## 118 4.2. Dynamic analysis

119 Apart from the effect of worn depth, four pairs of strain rate are taken into account based on the assumption of perfect  
 120 bond between prestressing wires and concrete. Table 3 shows the ultimate moment capacities of prestressed concrete  
 121 sleepers under impact loading at different strain rate.

122 Table 3. Ultimate moment capacities of prestressed concrete sleepers under impact loading.

Worn depth (mm)		Recorded moment capacity (kN-m)							
		A		B		C		D	
Railseat	Soffit	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
No abrasion		69.50	56.40	70.90	57.30	71.50	57.90	72.00	58.20
10	0	62.30	56.10	63.30	57.10	64.00	57.60	64.40	58.00
20	0	54.90	55.90	56.00	56.90	56.50	57.30	56.90	57.80
30	0	47.90	55.70	48.80	56.80	49.30	57.10	49.70	57.50
0	15	69.30	45.40	70.40	46.30	71.10	46.70	71.50	47.10
0	30	68.80	35.30	69.90	36.00	70.60	36.40	71.00	36.70
0	45	68.30	26.20	69.30	26.80	69.90	27.30	70.40	27.50

123 In case of railseat abrasion, it can be observed that moment capacities of worn sleepers are about 70% and 99% for  
 124 normal and inverse position, respectively, of moment capacities of full cross-sectional area by increasing of 30 mm in  
 125 worn depth. As for soffit abrasion, about 98% and 60% of moment capacities in full cross-sectional area are observed  
 126 when worn depth reaches 45 mm.

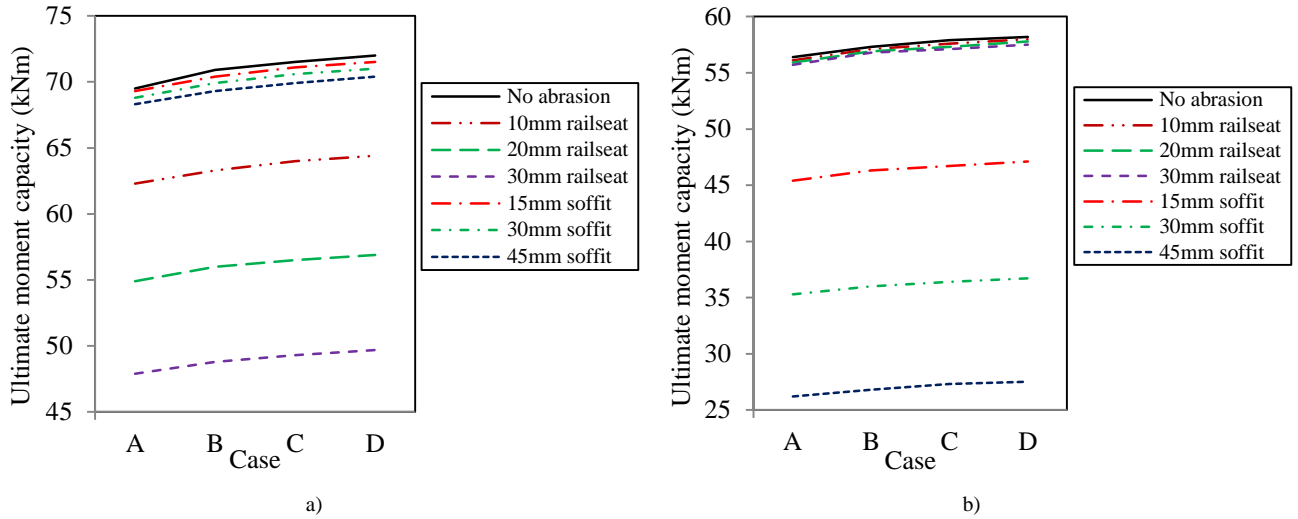


Fig. 3. Ultimate moment capacity at different strain rates in a) positive b) negative

As for strain rate, it can be seen from Fig. 3 that strain rate also play a role in moment capacity in concrete sleepers. The moment capacity show an upward trend when the strain rates increase with the same rate at any cases of mechanisms.

#### 4.3. Parametric study

##### 4.3.1. Uniform loss of prestressing steel

The concrete covering (effective anchorage zone) reduces and can induce the significant losses in prestressing steels, <sup>28,29</sup>. Loss can be expressed as percentage or in terms of stress or in terms of total deformation or in terms of strain. From literature, the cases when the prestressing was reduced to zero, but the tendons remained at full strength, did not result in a significant impact on the failure pressure, <sup>30-31</sup>. Hence, in case of 100% loss, it is assumed that tendons still remain in prestressed sleepers. The percentages of loss are expressed as proportion of prestrain in steel tendon. These comparisons provide insight into the importance of uniform prestressing loss. The strain rate of 2 and 6 for concrete and prestressing steel, respectively, are chosen. The uniform prestressing losses varied from 20% to 100% are considered in this study.

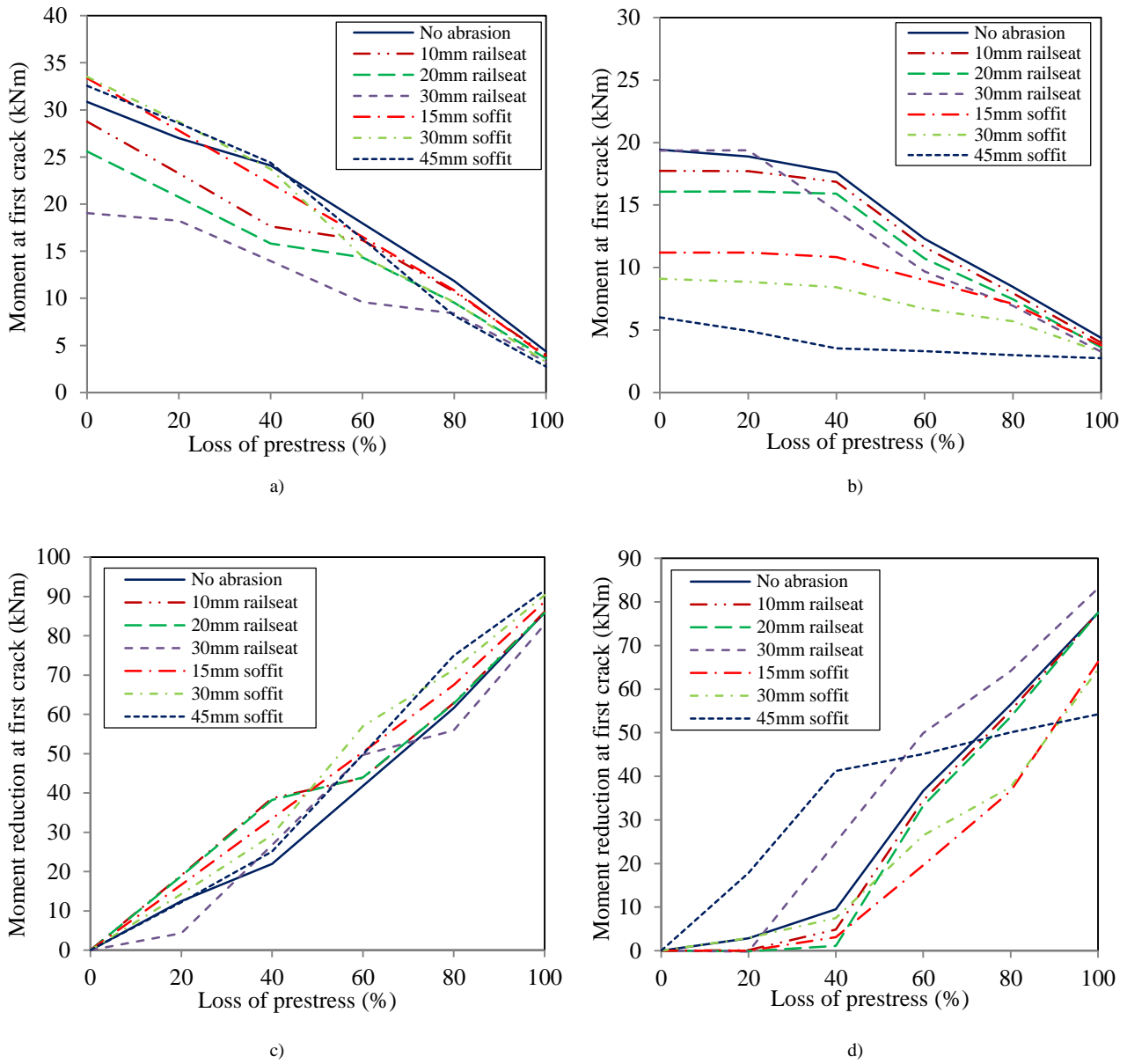


Fig. 4. a) Positive b) negative yield moment and c) positive d) negative yield moment reduction due to prestressing loss

In case of positive moment at first crack, Fig. 4a shows that loss of prestressing steel play a significant role as can be seen from 19-33kNm with no loss to around 5 kNm with 100% loss in all cases. About 30-40% and 80-90% positive moment reduction at first crack are observed in cases of 50% and 100% losses of prestressing steel, respectively. Thus, there is no a significant different between railseat and soffit abrasions in positive yield moment reduction due to loss of prestressing. As for negative yield moment, it can be seen that loss of prestressing by 100% can reduce the yield moment from about 16-20kNm with no loss to about 5kNm in case of railseat abrasion. It should be noted that only moment capacity is considered in this study so that crack pattern occurred is only flexural crack. In all cases, first crack occur at the bottom layer of the concrete, which is the tension face and will extend up to the neutral axis at the ultimate moment state.



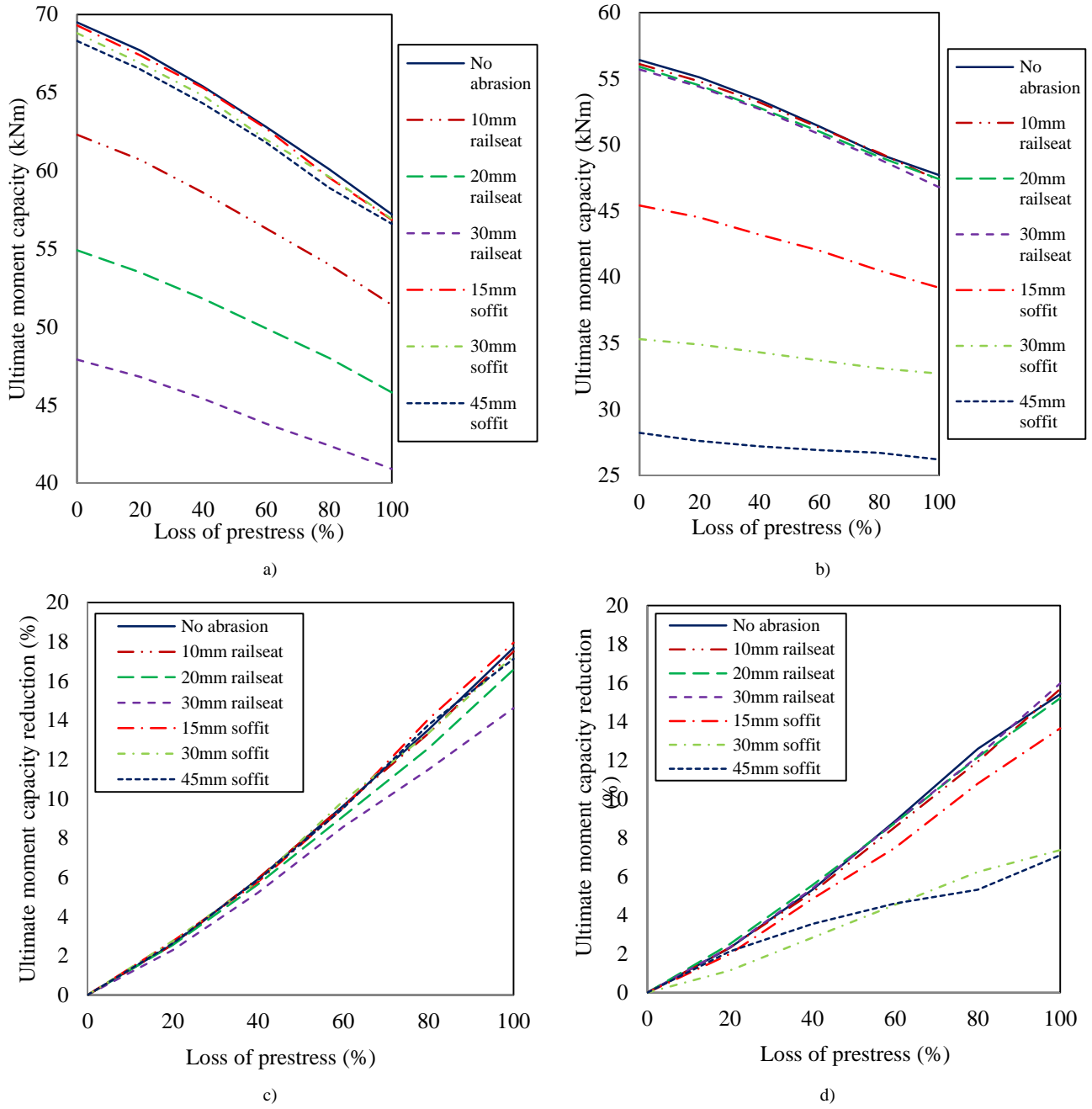
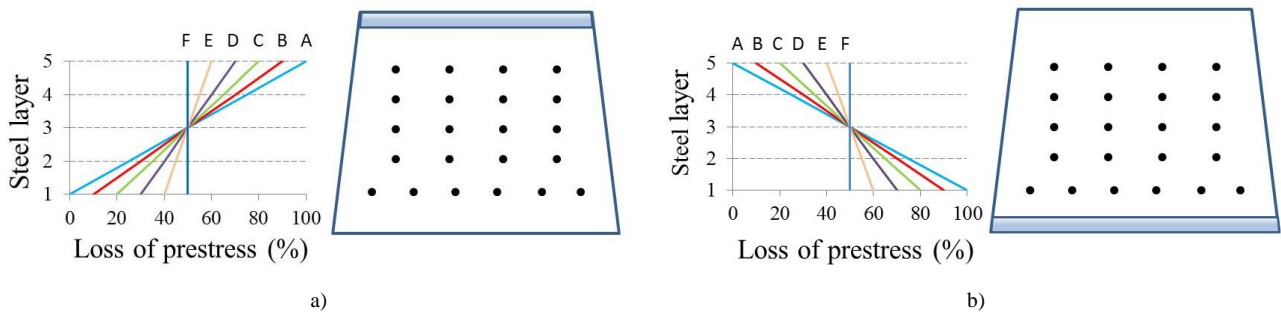


Fig. 5. a) Positive and b) negative ultimate moment c) positive and d) negative ultimate moment reduction due to prestressing loss

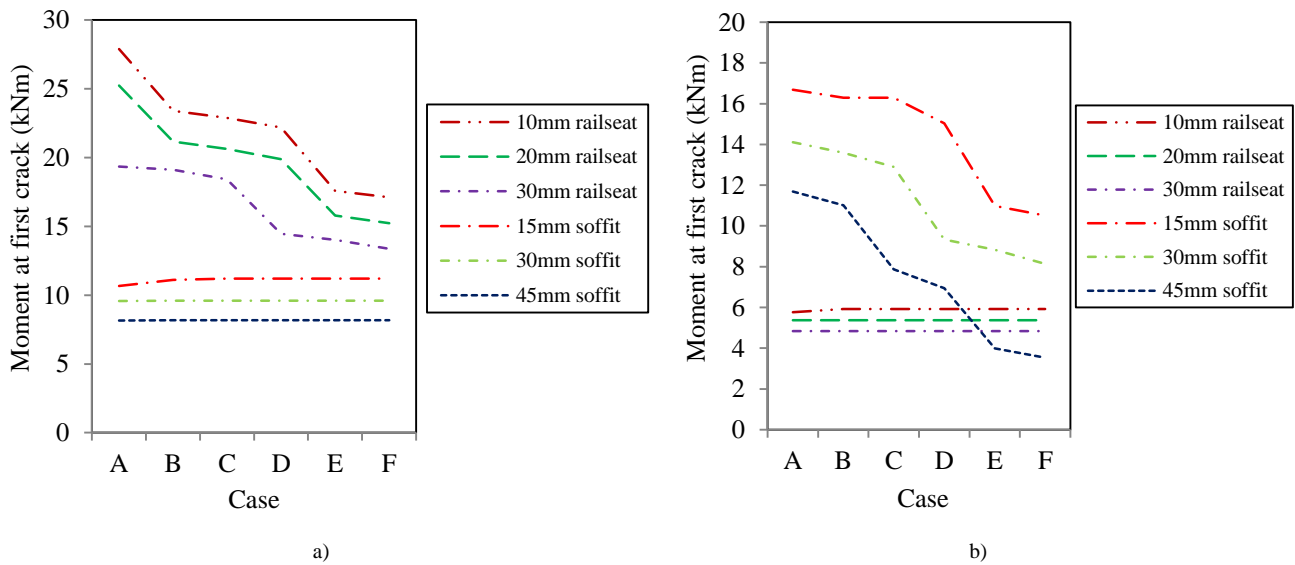
In case of positive ultimate moment capacity, increasing of prestressing loss by 100% can reduce the positive moment capacity by about 14-18% (Figs 5a and 5c). While, the negative ultimate moment capacity considering railseat abrasion can be reduced by about 14-16% by increasing prestressing loss by 100% (Figs 5b and 5d). However, loss of prestressing has a little influence on negative moment reduction as it can be reduced by only 7% and 13% for more than 30mm and 15mm soffit abrasions. Comparing the effect of prestressing loss on yield moment and ultimate moment, it is clearly seen that prestressing loss has more significant effect on yield moment by decreasing by almost 90% compared to 18% reduction in ultimate moment capacity.

### 159 4.3.2. Gradient loss of prestressing steel

160 The comparison of the case where the prestressing steel has the uniform prestress loss of 50% (Case F) to those cases  
 161 where the prestressing steel has the average gradient loss of 50% (Case A-E) are made how the moment capacity  
 162 changes with gradient prestressing loss. In case of railseat abrasion, it is assumed that prestressing loss increase over the  
 163 depth of sleepers from bottom to top layer as shown in Fig. 6a. Due to the decrease of concrete covering which lead to  
 164 the reduction of cross sectional area and the change of neutral axis, this also influences anchorage zone. This can affect  
 165 the creep and shrinkage of concrete which can also decrease the prestressing force in tendons near the edge of  
 166 sleepers,<sup>32,33</sup>. On the other hand, prestressing loss reduce over the depth from bottom to top layer in case of soffit  
 167 abrasion as shown in Fig. 6b.



168 Fig. 6. Analysis cases of moment capacity considering gradient loss of prestressing a) railseat abrasion b) soffit abrasion



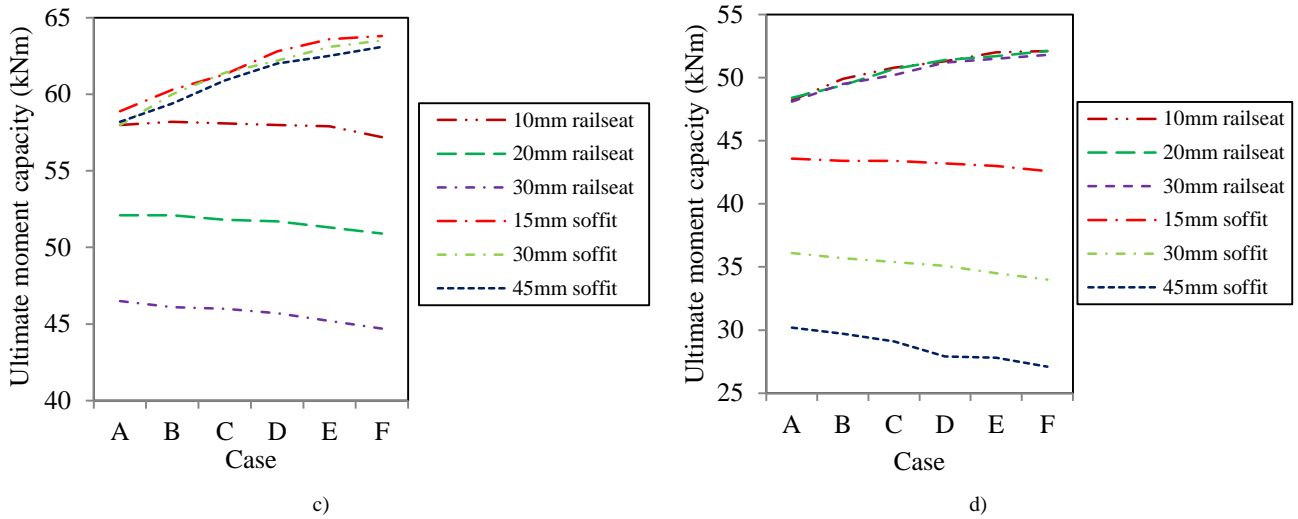


Fig. 7. a) Positive and b) negative yield moment c) positive and d) negative ultimate moment considering the effect of gradient loss

For positive moment at first yield in Fig. 7a, it is clearly seen that there is no significant effect of gradient loss of prestressing steel over sleeper depth in case of soffit abrasion. However, it should be noted that first crack can be observed at very low moment magnitude in all cases due to crushing of concrete as there are a high loss of prestress in all cases. As for railseat abrasion, the gradient losses of prestressing steel show a greater influence on positive yield moment as the uniform prestressing loss has the lowest positive yield moment. This is because concrete starts crushing earlier at the bottom fibre where the prestressing steel force reduces due to the higher prestressing loss. However, the gradient losses of prestressing steel do not have a significant impact on negative yield moment in case of railseat abrasion, which can be concluded as the same way as positive yield moment, as shown in Fig. 7b. Comparing the effect of gradient loss of prestressing on yield moment and ultimate moment, gradient loss has a little influence either on positive or negative ultimate moment capacities. Case A, which has highest gradient, show the maximum and minimum positive ultimate moment capacities in cases of railseat and soffit abrasions, respectively. However, Case F exhibit a totally difference results from Case A. In contrast, the minimum and maximum ultimate moment capacities in cases of railseat and soffit abrasion, respectively, are observed in Case A. Results of these are shown in Figs 7c-7d. The understanding into the dynamic capacity of railway concrete sleepers will also help improve technology for track condition monitoring,<sup>34-37</sup>.

## 5. Conclusions

This study is the world first to investigate the effect of surface abrasion on the impact capacity of railway prestressed concrete sleepers with the consideration of strain rate and prestressing loss effects. It exhibits that the surface abrasion undermines strength and impact capacity of railway concrete sleepers. It can be seen that the degradation of railway concrete sleepers in dynamic analysis has not been considered in previous research works. In fact, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. Therefore, it is essentially important for track and rail engineers to assure that the modification or retrofitting of concrete sleepers at construction sites is carried out in a proper manner. By the results obtained from these unprecedented studies, it is found that the soffit abrasion plays a

critical role on negative moment capacity reduction. On the other hand, railseat abrasion can reduce the positive moment capacity of the sleepers. Strain rate also play a role on the moment capacity under impact load. Moreover, prestressing loss has a significant effect on yield moment reduction. The 100%-uniform loss has about 90% yield moment reduction and 18% ultimate moment reduction.. Moreover, the gradient loss of prestressing has more effect on yield moment. It is noted that gradient loss has an effect on the increase of positive yield moment in case of railseat abrasion and negative yield moment in case of soffit abrasion. The insight into the impact behavior of the concrete sleepers with surface abrasion will enable safer built environments in railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice.

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